InfoCrop-cotton simulation model – its application in land quality assessment for cotton cultivation

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Crop simulation models have emerged as powerful tools for estimating yield gaps, forecasting production of agricultural crops and analysing the impact of climate change. In this study, the genetic coefficients for *Bt* hybrids established from field experiments were used in the InfoCrop-cotton model, which was calibrated and validated earlier to simulate the cotton production under different agro-climatic conditions. The model simulated results for *Bt* hybrids were satisfactory with an R^2 value of 0.55 ($n = 22$), d value of 0.85 and a root mean square error of 277 kg ha^{-1}, which was 11.2% of the mean observed. Relative yield index (RYI) defined as the ratio between simulated rainfed (water-limited) yield to potential yield, was identified as a robust land quality index for rainfed cotton. RYI was derived for 16 representative benchmark (BM) locations of the black soil region from long-term simulation results of InfoCrop-cotton model (based on 11–40 years of weather data). The model could satisfactorily capture subtle differences in soil variables and weather patterns prevalent in the BM locations spread over 16 agro-ecological sub-regions (AESRs) resulting in a wide range of mean simulated rainfed cotton yields (482–4393 kg ha^{-1}). The BM soils were ranked for their suitability for cotton cultivation based on RYI. The RYI of black soils (vertisols) ranged from 0.07 in Nimone to 0.80 in Panjari representing AESR (6.1) and AESR (10.2) respectively, suggesting that Panjri soils are better suited for rainfed cotton.

Keywords: *Bt* cotton, land quality, relative yield index, simulation model.

Introduction

CROP simulation models predict crop performance in relation to individual land qualities like moisture supply, nutrient supply and radiation balance that contribute to crop growth and yield[1]. They are employed in land evaluation to quantify production under potential and growth-limiting situations[2]. Models are also used to quantify the effects of moisture stress, nutrient stress, soil erosion, genotypic response and greenhouse gas (GHG) emissions under different land use and management regimes. The simulation models are the most reliable tools for estimating potential and water-limited yields because they accurately account for variations in weather across years and locations, consider interactions among the crop,

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*For correspondence. (e-mail: mvvenugopalan@gmail.com) weather, soil and management, and allow quantification of both potential and water-limited yields[3]. This would not otherwise be possible with empirical tools.

Several generic and crop-specific simulation models have been developed for field and horticultural crops. In cotton, SIMCOT[4], GOSSYM[5], COTTAM[6], OZCOT[7], SUCROS-cotton[8] and a few others are developed and used as research and decision-making tools. InfoCrop, a simple, indigenous generic model was developed for subtropical and tropical environments and applied for several field crops[9]. This model was calibrated with genetic coefficients for cotton and validated using extensive experimental data[10]. This InfoCrop-cotton model was later applied for regional-level prediction of cotton production[10], soil site suitability evaluation[11] and assessing the impact of climate change[12]. New genetic coefficients were developed for *Bt* hybrids[12], since these hybrids have now replaced the conventional varieties and hybrids in over 90% of the cotton area of 117 lakh ha (ref. 13). The present study validates the *Bt* version of InfoCrop-cotton and employs this for estimating potential and water-limited yields.

Most of the world's cotton is produced in arid and semi-arid climates by resource-poor farmers. In India, its cultivation also extends to dry, sub-humid regions. Cotton is the source of livelihood for 100 million family units engaged directly in its production and another 150 million people engaged in ancillary activities – transportation, ginning, baling and storage[14]. Being a commercial crop, cultivated predominantly under rainfed conditions, it is important to develop a reliable land quality indicator to compare rainfed cotton production sites and monitor changes in their quality with time under different sets of management.

The current quality of the land as well as the likely changes in its quality with time are of interest to researchers and policy makers. Land quality indicators are needed for assessing and monitoring land quality in spatial and temporal dimensions[15,16]. Moreover, land quality must essentially be assessed with reference to specific land use[17]. We adopted the classical concept of production hierarchy[18] in defining a land quality indicator and utilizing it for assessment. In this concept, the factors of production may be growth defining, growth limiting or growth reducing. Growth-defining factors that determine the potential (or maximum) productivity are radiation, temperature, CO_2 concentration and crop varietal characteristics. Growth-limiting factors include water and nutrients[19].

The use of simulation modelling of crop growth and solute fluxes has been suggested to define a land quality expressed as the ratio between a conditioned crop yield and potential yield × 100 (ref. 17). This concept is more applicable to humid tropics, where leaching of nutrients under the influence of high rainfall may aggravate soil degradation and offset the benefits of rainfall in increasing water-limited yields. Earlier, the ratio of actual and potential yields was proposed as a useful land quality indicator[20]. However, actual yields are influenced by several controllable and uncontrollable factors and it is often difficult to obtain accurate data on actual yield (except from field experimental records). Hence the present article adopts a relative yield index (RYI), defined as the ratio between the simulated water-limited (rainfed) yield to potential yield, as a simple land quality indicator. Both potential and water-limited (rainfed) yields for any location can be determined using simulation models utilizing historical long-term weather data and soil properties. We employed the RYI derived through InfoCrop-cotton model to assess the quality of land in 16 benchmark locations of the black soil region (BSR) for a specific land use, i.e. rainfed cotton (*Bt* hybrid) cultivation and also ranked these locations based on their suitability to support rainfed hybrid (*Bt*) cotton cultivation.

Materials and methods

Model description

InfoCrop-cotton is a constituent of InfoCrop, a generic model developed to simulate the effects of weather, soil, agronomic management and major pests on crop growth and yield. The basic crop model software is in Fortran Simulation Translator programming language (FST/FSE; Graduate School of Production Ecology, Wageningen, The Netherlands)[21]. Detailed description of the model framework, its validation and application are described elsewhere[9,22] and the model has been calibrated and validated for cotton crop[9]. InfoCrop-cotton model[10] with genetic coefficients for Bt hybrid was used in the present study.

Validation of InfoCrop-cotton model for Bt hybrids

The InfoCrop-cotton model was validated using results of two replicated field experiments: (i) optimization of irrigation and nitrogen requirement for increasing the input use efficiency of a medium-duration *Bt* cotton hybrid (RCH 2B; under winter irrigated conditions at Coimbatore, Tamil Nadu, 11°00′N and 77°00′E) and (ii) synchronizing nitrogen and potassium supply with crop demand to enhance productivity and nutrient-use efficiency of a medium-duration *Bt* hybrid, Bunny *Bt* (under rainfed conditions at Nagpur, 21°09′N, 79°09′E) conducted during 2006–2007 and 2008–2009. The data from the replications were averaged for calculating the residuals. The soil of the experimental site at Coimbatore was a mixed red and black clay loam (Vertic Ustropepts) and that at Nagpur was a deep cracking clay soil (Typic Haplusterts). The input data for running the model – date of sowing, seed rate, date and rate of fertilizer application and irrigation (at Coimbatore) were according to the technical programme implemented in the experiments[23,24]. Simulations were done for different N (0, 60, 90 and 120 kg N/ha) and irrigation (no irrigation, 0.6, 0.8, 1.0 Irrigation Water/Cumulative Pan Evaporation (Iw/CPE) irrigation) for irrigated experiment and for N application schedules (N @90 kg/ha was applied in two splits (10, 30 days after sowing (DAS)), three splits (10, 45 and 75 DAS, 10, 30 and 60 DAS, 10, 30 and 75 DAS) or four splits (10, 20, 45 and 60 DAS, or 10, 20, 45 and 75 DAS) for rainfed cotton experiment. Soil data from the site of experimentation were used for preparing soil input files. Daily weather data recorded at both the experimental sites were used for simulation.

The fit between observed and simulated values was evaluated using R^2, root mean square error (RMSE), model efficiency (ME; commonly known as Nash–Sutcliffe efficiency) and index of agreement (d). RMSE is commonly used in model calibration and validation and is a measurement of bias. RMSE values of 0 indicate a perfect fit. Lower the RMSE, better the model simulation performance. ME is a normalized statistic that determines the relative magnitude of the residual variance ('noise') compared to the measured data variance ('information')[25]. ME ranges between $-\infty$ and 1.0 (1 inclusive), with ME = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas those < 0.0 indicate that the mean observed value is a better predictor than the simulated value, which shows an unacceptable performance. The index of agreement was developed by Willmott[26] as a standardized measure of the degree of model prediction error and varies between 0 and 1. A computed value of 1 indicates perfect agreement between the measured and predicted values, and 0 indicates no agreement at all[26]. These indices were computed using the following equations

$$\text{RMSE} = \sqrt{\frac{\sum(\text{Observed} - \text{simulated})^2}{\text{Number of observations}}},$$

$$\text{ME} = \left[1 - \frac{\sum(\text{Observed} - \text{simulated})^2}{\sum(\text{Observed} - \text{mean}_{\text{observed}})^2}\right],$$

$$d = \left[1 - \frac{\sum(\text{Observed} - \text{simulated})^2}{\sum(|\text{Observed} - \text{mean}_{\text{observed}}| + |\text{simulated} - \text{mean}_{\text{observed}}|)^2}\right].$$

Characteristics of benchmark sites

Sixteen benchmark locations in major agro-ecological sub-regions (ARSRs) representing rainfed cotton-based cropping system in BSR (Table 1) were selected for the present study. The soils were either Vertisols or vertic intergrades. Two subunits each experience a sub-humid moist, sub-humid dry and arid dry bioclimate and the remaining 10 have a dry semi-arid bioclimate. It is also evident from Table 1, that cotton is a dominant crop of these locations.

Development of land quality indicator

To simulate the potential and water-limited yields in all the benchmark sites, weather and soil files in InfoCrop format, were developed. Daily weather data collected from India Meteorological Department, Pune and All-India Coordinated Research Project on Agro-meteorology, Hyderabad observatories located nearest to the benchmark locations were used for simulation using InfoCrop-cotton. Depending upon the availability and completeness (Table 2), daily data for periods ranging from 11 to 40 years were used to prepare weather files. Daily weather data on sunshine hours, maximum and minimum temperature, wind speed, vapour pressure and rainfall were compiled, converted into InfoCrop weather files and used for simulation. Basic data on physical (particle size, depth, soil moisture constants, slope and saturated hydraulic conductivity (sHC)) and chemical (organic carbon, pH and electrical conductivity) properties for the benchmark locations were used[27]. Weighted mean of the horizon-wise data was transformed into a three-layer InfoCrop format for preparing the respective soil master files. The recommended crop management data-seed rate (2 kg/ha), sowing depth (4 cm) and the most appropriate sowing date for each location were used to simulate both potential and water-limited (rainfed) yields. Since the data on wind speed and vapour pressure were available for all the weather datasets, modified Penman option was used for calculating potential evapotranspiration (PET). While simulating potential yield, the options for irrigation and nitrogen were not selected. While simulating water-limited yields, the option for simulating unirrigated crop was exercised. Similarly, the option for not considering nitrogen stress was selected. Information on nutrient supply and pest incidence was not required, because it is assumed that these factors do not influence water-limited yields (rainfed yields). At the water-limited yield level, it is assumed that nutrient availability will not limit crop growth[28].

In all 648 simulations were run across 16 benchmark locations to derive values for potential and water-limited yields. The RYI was calculated as the ratio of the mean (over years) water-limited seed cotton yield to mean potential yield.

Results and discussions

Validation of the model

The results of validation of InfoCrop-cotton model with genetic coefficients of a typical medium-duration *Bt*

Table 1. Characteristics of benchmark soils and their areal extent

AESR	Soil series	Location	Soil taxonomy	Area covered by AESR (ha)	Area under cotton (ha)
Sub-humid moist (SHm)					
7.3	Tenali	East Godavari (Andhra Pradesh)	Sodic Haplusterts	3,508,137	232,500
10.1	Nabibagh	Bhopal (Madhya Pradesh)	Typic Haplusterts	8,358,211	3,467
Sub-humid dry (SHd)					
10.2	Panjri	Nagpur (Maharashtra)	Typic Haplusterts	2,870,937	181,900
5.2	Sarol	Indore (Madhya Pradesh)	Typic Haplusterts	14,183,795	975,125
Semi-arid dry (SAd)					
6.3	Paral	Akola (Maharashtra)	Sodic Haplusterts	5,651,592	1,445,733
6.2	Vasmat	Hingoli (Maharashtra)	Typic Haplusterts	12,230,671	2,037,692
7.2	Kasireddipalli	Medak (Andhra Pradesh)	Typic Haplusterts	9,245,967	779,914
8.2	Sidlaghatta	Kolar (Karnataka)	Vertic Haplustepts	6,603,009	78,236
8.3	Kovilpatti	Tuticorin (Tamil Nadu)	Gypsic Haplusterts	8,935,407	78,500
7.1	Nandyal	Kurnool (Andhra Pradesh)	Sodic Haplusterts	3,974,579	36,000
5.1	Bhola	Rajkot (Gujarat)	Vertic Haplustepts	2,476,991	864,767
6.4	Achamati	Dharwad (Karnataka)	Sodic Haplusterts	5,515,361	341,196
3.0	Teligi	Bellary (Karnataka)	Sodic Haplusterts	4,926,424	35,314
8.1	Coimbatore	Coimbatore (Tamil Nadu)	Typic Haplusterts	3,470,381	20,667
Arid (A)					
5.3	Sokhda	Rajkot (Gujarat)	Leptic Haplusterts	568,914	542,834
6.1	Nimone	Ahmadnagar (Maharashtra)	Sodic Haplusterts	7,520,283	296,264

Table 2. Meteorological data used for simulations

Series	Met station	Period (years)	Years of simulation	Series	Met station	Period	Years of simulation
Sarol	Indore	1975–2004	30	Nabibagh	Bhopal	1969–2003	29
Paral	Akola	1969–2008	40	Nimone	Rahuri	2001–2010	10
Kasireddipalli	Hyderabad	1975–1999	25	Achmatti	Dharwar	1990–2005	16
Coimbatore	Coimbatore	1962–2008	32	Sokhda	Rajkot	1989–2003	15
Kovilpatti	Kovilpatti	1985–2001	17	Nandyal	Nandyal	1984–2003	20
Bhola	Rajkot	1989–2003	15	Sidlaghatta	Kolar	1991–2001	11
Vasmat	Parbhani	1992–2007	15	Panjri	Nagpur	1990–2012	23
Tenali	Guntur	1995–2007	13	Teligi	Bellary	1994–2006	13

hybrid for seed cotton yield are presented in Figure 1. The values of correlation coefficients r and R^2 were 0.74 and 0.55 respectively, indicating a high degree of colinearity between observed and simulated values. A model with R^2 value of 0.5 and above is acceptable[29]. The RMSE for seed cotton yield was 277 kg/ha, which was 11.2% of the mean observed yields. Considering the variability in the growing conditions across two locations, the low values of RMSE obtained also reinforce the fact that the model results are acceptable. Further, the values were scattered on either side of the zero reference line, indicating that it was devoid of any systemic errors. The ME of the validation results was estimated as 0.52, which is positive and lies in the range 0.0–1.0, indicating that the model performance is quite satisfactory. The index of agreement value was 0.85, which is close to 1.0. Thus, the values of all the parameters used for validating the InfoCrop-cotton are within the acceptable range.

Potential and water-limited yields

The data on the mean simulated potential and water-limited seed cotton yields, along with the appropriate statistical measures of dispersion (range and coefficient of variation, CV) are presented in Table 3. The typical values of potential yield were higher than those of water-limited yields. If genetic traits of a cultivar and atmospheric CO_2 are kept constant, as done during the present investigation, potential yields are a function of solar radiation and temperature and are not dependent on soil properties, because it is assumed that both nutrients and water availability are non-limiting[3,28]. The potential seed cotton yields are location-specific due to climate variability. However, due to moderate differences in climatic parameters within the BSR, the mean potential yield varied over a narrow range from 4582 to 6306 kg/ha. The extent of variation within a location across years of simulation,

Table 3. Simulated potential and water-limited (rainfed) seed cotton yield (kg/ha) at benchmark locations

		Simulated crop yield (kg/ha)							
		Potential				Water-limited			
AESR no.	Soil series	Maximum	Minimum	Mean	CV(%)	Maximum	Minimum	Mean	CV(%)
Sub-humid moist (SHm)									
7.3	Tenali	5345	4747	4582	9.6	3780	825	1839	25.6
10.1	Nabibagh	5671	3884	4861	8.6	3809	924	2265	26.4
Sub-humid dry (SHd)									
10.2	Panjri	5940	4374	5437	2.9	5936	313	4393	23.1
5.2	Sarol	5927	3830	4858	12.0	4486	2111	3552	17.6
Semi-arid dry (SAd)									
6.3	Paral	5949	3803	5237	10.2	4340	914	2667	35.9
6.2	Vasmat	5949	4477	5445	15.4	5918	1120	2712	40.7
7.2	Kasireddipalli	5954	4736	5519	7.8	5160	3361	4081	20.62
8.2	Sidlaghatta	6591	6508	6560	4.6	5493	335	2860	47.8
8.3	Kovilpatti	5974	4859	5547	7.3	4380	175	2712	49.3
7.1	Nandyal	5913	4910	5365	6.42	1884	290	998	60.7
5.1	Bhola	5822	4081	5018	9.7	2682	684	2860	29.7
6.4	Achmatti	5964	4254	5587	10.1	5181	280	3569	45.7
3.2	Teligi	4970	4182	4690	5.7	4842	212	1823	61.0
8.1	Coimbatore	6012	3648	5356	12.1	2581	175	1506	66.3
Arid (A)									
5.3	Sokhda	5822	4081	5018	9.7	2090	287	1306	76.5
6.1	Nimone	6583	5651	6306	4.6	1598	202	482	81.3

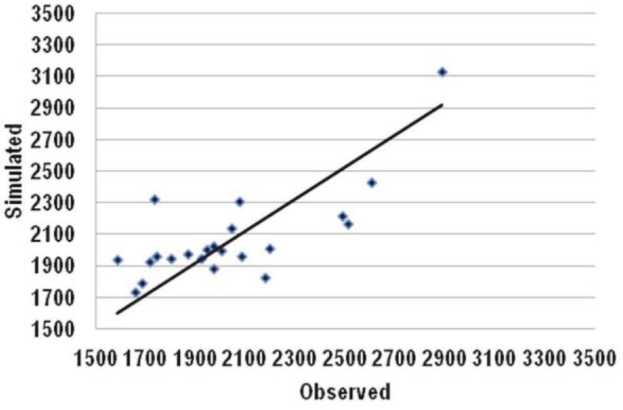

Figure 1. Relationship between observed and simulated seed cotton yield (kg ha^{-1}).

is attributable to the annual variations in radiation and temperature regimes. Across locations the difference in potential yield is attributed to latitudinal variation, which in turn influences the incident solar radiation and temperature. Nevertheless, these differences were narrow with lower CV compared to water-limited (rainfed) yield.

The mean water-limited (rainfed) seed cotton yield ranged from 482 kg/ha in Nimone (Ahmednagar) to 4393 kg/ha in Panjri (Nagpur). Across bioclimates, the mean values of water-limited (rainfed) yield were higher under dry sub-humid bioclimate compared to moist sub-humid and semi-arid and arid bioclimates. In all the bioclimatic regimes, the water-limited yields were lower than the corresponding potential yields, because water supply is never optimal and both excess and deficit soil moisture decreases seed cotton yields. When water supply through rainfall is insufficient to meet the evapotranspiration (ET) demand of the crop, the actual ET will be lower than the PET, resulting in water stress. Depending upon the timing of water stress, duration of stress and stage of the cotton crop, the yield was reduced to varying degrees.

Water-limited yields of benchmark locations of semi-arid and arid bioclimates were characterized by a higher CV, and this underlies the typical risks associated with rainfed cotton cultivation. For non-*Bt* cotton, the rainfed water-limited yields ranged from 900 to 2400 kg/ha with CV ranging from 12% to 74% (ref. 30). In locations like Sokhda (Rajkot), Nimone (Ahmednagar), Teligi (Bellary), Coimbatore, the mean seasonal rainfall was less than 525 mm, the simulated water-limited yields are low and CV is high. Thus, the farmers generally grow cotton, only where irrigation facilities are available to supplement the soil moisture supplied through rainfall. Simulated water-limited yields are influenced by rainfall and soil profile characteristics. The latter governs the quantity of rainwater entering the soil, which can be utilized by the crop during its growth and development period. The InfoCrop-simulated water-limited yields do not take into account the nutrient leaching and soil erosion, which may be aggravated with high rainfall, a characteristic of humid tropics, but cotton is seldom cultivated in these regions in India. In Vertisols, the soil water dynamics is governed by exchangeable sodium percentage (ESP) and sHC of the soil[31]. Data on rainfall during crop simulation period,

Table 4. Rainfall during crop growing period, saturated hydraulic conductivity (sHC) and exchangeable sodium percentage (ESP) of soils at different benchmark locations

AESR no.	Soil series	Rainfall (mm) Mean	CV	sHC (mm h^{-1})	ESP
7.3	Tenali	751	25.03	18.7	8.4
10.1	Nabibagh	965	21.10	15.3	0.9
10.2	Panjri	907	26.44	10.3	0.9
5.2	Sarol	878	30.41	9.4	3.6
6.3	Paral	630	28.24	8.9	11.6
6.2	Vasmat	795	31.98	6.2	5.1
7.2	Kasireddipalli	877	25.58	15.4	5.3
8.2	Sidlaghatta	733	22.29	9.6	9.3
8.3	Kovilpatti	467	37.72	4.5	1.0
7.1	Nandyal	738	47.64	2.0	17.7
5.1	Bhola	368	49.25	7.2	6.6
6.4	Achmatti	555	31.16	4.2	6.2
3.2	Teligi	483	74.15	12.2	7.8
8.1	Coimbatore	525	26.63	19.5	1.9
5.3	Sokhda	368	49.25	13.9	16.2
6.1	Nimone	401	42.94	4.9	7.5

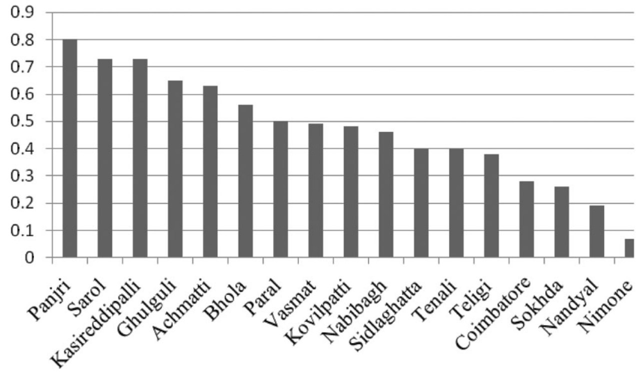

Figure 2. Relative yield index of cotton in different benchmark soils in the black soil region.

sHC and ESP are presented in Table 4. Water-limited (rainfed) seed cotton yield had a significant positive correlation ($r = 0.52$) with rainfall during the crop simulation period, expectedly because rainfed cotton production in Vertisols is primarily a function of the quantum and distribution of rainfall[32]. A significant negative correlation between yield and ESP ($r = -0.46$) was observed, and therefore benchmark locations where the soil was sodicVertisols, viz. Paral, Vasmat and Nandyal had lower water-limited (rainfed) yields compared to non-sodic soils of the same bioclimatic regime, except Teligi (where the rainfall was sub-optimal). In practice, ESP disperses clay particles, impairs soil moisture infiltration[33] and reduces moisture availability, thereby lowering yields. The relationship between simulated water-limited seed cotton yield and sHC was quadratic ($r = 0.45$) with an optimum value of sHC of 10.6 mm/h. sHC and ESP along with $CaCO_3$ in clay fraction and Ca/Mg ratio influenced the yield of rainfed cotton in Vertisols of Central India[33]. It was found that a sHC value of 10 mm/h was the critical limit, below which water movement into the soil profile of Vertisols and vertic intergrades was severely impaired[34].

Relative yield index as land quality index

Land quality indices (LQIs) should function as reliable indicators for comparing and monitoring the quality of land resource with reference to a specific land use. Figure 2 ranks the benchmark locations based on the values of RYI derived from the potential and water-limited (rainfed) seed cotton yields simulated using the InfoCrop-cotton model. The values of RYI ranged from 0.80 at Panjari (Nagpur) to 0.07 at Nimone (Ahmednagar). The water requirement of a typical cotton crop is around 800 mm in Central India. Soils of Panjari (Nagpur) and Sarol (Indore) are very deep and well drained and have the ability to store sufficient water in the profile. Rainfall during the cotton-growing season ranged from 616 to 1668 mm in Nagpur and 566 to 1425 mm in Indore. During those years, when the rainfall was well distributed and the soil profile had ample moisture to meet the demand of cotton crop during the post-rainy period, no moisture stress was observed. Under such situations, the water-limited yields tend to match the potential yield. In regions with high rainfall, the water-limited yields may approach the potential yield[17]. Five benchmark soils, viz. Panjari (0.80), Sarol (0.73), Kasireddipalli (0.73), Achmatti (0.63) and Bhola (0.56) had LQI above 0.5, indicating their suitability over others to support rainfed cotton production. Four benchmark soils, viz. Coimbatore, Sokhda, Nandyal and Nimone had RYI lower than 0.3.

Large differences in rainfall and soil hydraulic properties (Table 4) across benchmark locations resulted in wide variation in water-limited yields and in turn the RYI. The RYI could satisfactorily capture subtle differences in soil variables and weather patterns prevalent in the BSR.

Moreover, we propose that the RYI is a robust LQI for rainfed cotton and is easy to estimate using InfoCrop-cotton model. It will serve as a useful tool for comparing locations for their suitability for rainfed cotton production and will also help in monitoring the changes in land quality over time in response to the land management options adopted.

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